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BEHAVIOR OF COMBINED DIELECTRIC-METALLIC SYSTEMS IN A CHARGED PARTICLE ENVIRONMENT

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ABSTRACT

In the continuing effort to simulate discharges seen during geomagnetic substorms, the charging and discharging characteristics of an electrically isolated solar array segment are being studied. A solar array segment is floated while bombarded with monoenergetic electrons at various angles of incidence. The potentials of the array surface and of the interconnects are monitored using Trek voltage probes, to maintain electrical isolation. A back plate is capacitively coupled to the array to provide information on the characteristics of the transients accompanying the discharges.

Several modes of discharging of the array were observed at relatively low differential and absolute potentials (a few kilovolts). A relatively slow discharge response in the array was observed, discharging over one second with currents of nanoamps. Two types of faster discharges were also seen which lasted a few hundredths of a millisecond and with currents on the order of microamps. Some observations are reported which indicate an electron emission process associated with the arcs.

I. INTRODUCTION

Analytical predictions of solar array potentials in geomagnetic substorm environments have indicated that solar cell cover slides are at a positive potential with respect to the interconnects (refs. 1,2). This has been called the inverted gradient mechanism (ref. 3). Since the distances between them are small it is believed that such voltage distributions can give rise to breakdowns, which could produce the spacecraft charging anomalies observed in satellites. The initial purpose of this work was to evaluate further the plausibility of this mechanism. By varying the angle of incidence of the electron beam, it was thought that the amount of differential charging could be varied, and information obtained about arc conditions could be used to evaluate the inverse gradient mechanism. Some of the information presented in this report has been presented earlier (ref. 4).

Discharges have been generated in laboratories in the past by irradiating solar arrays with electron beams. However, the interconnect circuits have been either grounded (refs. 5,6), biased (ref. 3), or floated on a large resistor (ref. 7). Each of these techniques has yielded useful information, but these test results may have been influenced by the test arrangement which affected the amount of charge on the interconnects.

This work represents another step in attempting to simulate environmentally induced discharges. A small solar array segment is electrically floated and irradiated by a monoenergetic electron beam. Since the array is now isolated the progress of the discharge can be watched through a back plate. The plate on the back of the array mounting is used as a capacitively coupled probe, to monitor the changing array potential as charge leaves the array during discharges. The voltage of the array is determined only by the charge stored on it and its capacitance. The fraction of the charge lost can be determined easily by the fraction of the voltage change. The change in voltage is reflected by a change in the back plate potential. This is simpler than

trying to catch all the charge.

In this report, the details of the test apparatus are described, the surface voltage profiles as a function of beam angle of incidence are discussed and the discharge transient characteristics are presented. The results from the biased array are presented to provide a comparison with floating array results.

II. EXPERIMENTAL APPARATUS

This work was conducted in one of the large vacuum chambers (2.1 m x 1.05 m diameter) at NASA LeRC. The chamber is an ion pumped system. During these tests the pressure was typically 1.5 x 10^{-4} Pa. The electron gun used a hot filament to produce electron densities of up to 15 nA/cm^2 over an area of 300 cm^2, at energies up to 10 KeV.

An unexpected side effect of working in the ion pumped system is the existence of a high resistance electrical connection to ground, i.e., the tank walls. This has a pressure dependence and is probably due to a weak plasma produced by the ion pump. At 1 x 10^{-6} Torr an electrometer measures this resistance as 3 x 10^{10} ohms. This indicates the existence of a residual plasma, which may interact with the array along with the electron gun. This fact has to be remembered when deciding whether the arcing observed was due solely to an electron beam interaction.

The solar array segment (fig. 1) used for these experiments was from the SPHINX satellite, and has been used in similar testing before (ref. 3). It is constructed from 24, 2 cm square solar cells connected in series to form a 6 x 4 matrix. The interconnects are a silver mesh, and the cover slides are 0.15 mm thick, fused silica. The gap between the cells for the interconnects is 0.5 to 1 mm wide. This assembly is attached to a sheet of Kapton which in turn is attached to a 0.16 mm fiberglass printed circuit board. A 2.5 cm radius copper disk has been etched on the back of the board near the center of

the array, and covered with Kapton. This back plate serves as a capacitively coupled probe (65 pF) which is used to monitor the time dependence of discharges on the array.

The array is mounted on a rotatable platform (fig. 2(a)) so that the angle of incidence of the electron beam can be varied. This provides a method of attempting to vary the electrical potential profile of the array.

The potentials along the array were measured using a noncontacting Trek electrostatic voltage probe. Two probes were employed in this work. One probe was located above the array and was capable of moving along a column of cells. It obtained profiles of the surface potential along that column. The second probe monitored the potential of the array interconnects. A shielded cable ran from the interconnects to the probe which was located outside the vacuum system. A test was made using the probe inside the vacuum system to monitor the interconnects to ensure that using a probe outside the system would have no effect on the characteristics of the discharges. These tests were run with this connection immediately behind the array inside the system (shielded from direct interactions with the beam). In addition, it was possible to connect a power supply to the interconnects to evaluate the behavior of the array with the interconnects biased negative with respect to the cover slides.

To evaluate the electrical characteristics of the back plate/array capacitor, a square voltage pulse was applied to the interconnects of the array. The back plate was connected to an oscilloscope with a 1 megohm input impedance. The decay observed in Fig. 2(b) is consistent with an RC discharge with a time constant of 0.7 milliseconds. The voltage of the back plate rises with with the input pulse to within a tenth of a microsecond. This determines the fastest signal that can be followed. The loss in signal was due to additional capacitances between the cable and its shield (700 pF). The capacitance

between the back plate and the interconnects was found to be 65 pF, from the loss in signal. Comparisons of the signal loss for different cables verified this. For fast discharges (t << RC) the currents can be calculated from the peak voltage (charge lost) and the rise time. For slow discharges (t >> RC) the current is voltage/1M ohm.

III. RESULTS

A. Potential Along the Array

The intention of this work was to produce an inverted potential gradient (the interconnects more negative than the glass) in the vicinity of the interconnect by increasing the secondary yields of the cover slides. This could produce an intense electric field at the cover slide/interconnect boundary, and might allow charge to escape from the interconnects via a field emission mechanism. It was assumed that this could be done by increasing the angle of incidence between the sample and the electron beam. Increasing the yield should make the equilibrium potential of the glass more positive. Clean metals typically have lower yields than insulators (less than one) and should remain at nearly the beam potential. This process should have served to enhance the difference between the metal and glass potentials. However, this did not happen.

Figure 3 demonstrates the angular dependence of the surface potentials on the angle of incidence for a 5 Kev electron beam. At normal incidence, the cover slides reached a potential of about -3 KV. The interconnect was at a potential of -1 KV, substantially more positive than expected from the secondary yield of metals. This was probably due to capacitive effects.

The back plate-solar cell-cover slide system may act like a capacitive voltage divider. Since the interconnects have a small exposed surface area they have a large effective resistance to the plasma. Yet since the "conductor" area includes the semiconductor of the solar cells this capacitance

is comparatively high. There is a capacitance to the back plate also. It appears that the floating interconnect acts as a voltage divider, and maintains a potential between the cover slides and the back plate.

However, from this capacitance argument it would be expected that the interconnects would be closer to the cover slide potential than to the back plate. The current collection mechanism from the plasma may also have an important contribution to the determination of the equilibrium potential.

Increasing the angle of incidence forces the cover slides more positive as expected from the effect of angle of incidence on secondary yields. However, the interconnect potential does not approach the beam energy as anticipated. This may be due to either of two reasons. The beam may be deflected by the electric fields at the edges and does not reach the interconnects disrupting the charge collection mechanism, or the interconnects may have secondary yields significantly different from those for pure silver. In recent work, Hoffman and coworkers (ref. 8) have noted that the secondary yield for aluminum on Kapton tends to look more like aluminum oxide than aluminum. The silver interconnects in this case may have contaminants on the surfaces, increasing the secondary yields.

Another interesting feature in the potential profiles is the negative peak at the edge of the cover slide. This feature is consistent with an edge effect generated by Reeves and Balmain (ref. 9) in a two dimensional charging model of an electron beam impinging on a dielectric mounted on a metal. It is related to the focusing of the beam at the edge. To check whether or not this was a feature of the interconnect geometry, the probe was moved to an adjacent column where the geometry is reversed. The peak stays on the edge of the glass facing the beam, rather than follow the interconnect geometry. This tends to increase the electric field near the interconnect region. This edge effect provides an inverted gradient, but there is insufficient charge stored

on the edge to account for the observed discharges. The inverted gradient is clearly not the sole criteria for the occurrence of discharges.

The attempt to create an inverted potential gradient at the interconnect was unsuccessful. If the inverted potential gradient is the dominant arc mechanism, discharges should not have occurred. However, discharges were observed.

B. Discharges - Floating Array

Several forms of discharge are seen on the floating array. First, the slow discharges will be discussed (Table I). These are more of a de-charging process than an arc. Then the fast discharges will be discussed (Table II).

The results in Table I and II were obtained from a series of runs to determine the dependence of the discharges on beam energy, current density and angle of incidence. These tables were obtained by choosing an energy and angle of incidence. Beginning at a low beam current density, the beam current was held constant for about 1000 s, or until a reasonable number of discharges were observed, before increasing to a larger current. Since the charging at lower currents was not clearly separated from those at higher currents, the discharge rates are given as a function of energy and angle only. The rate is given as a ratio of the number of discharges observed to the time that it took to run the test. These data should not be taken as particularly reproducible since the interconnect potential obtained at the end of this process disagreed with that obtained at the beginning. In addition, conditions which originally produced discharges on this solar cell array, no longer do.

1. Slow Discharges.

Table I illustrates how these slow arcs depend on various conditions. At low current densities discharges were not seen. In the beam current range of 2-5 na/cm^2, slow repetitive discharges occurred. At higher current densities, array could discharge slowly but not recharge. Then an equilibrium

potential closer to ground would be maintained. At other times, as the array initially charged it charged to a relatively low value, rather than dropping to it. Once this low potential is reached, the interconnect potential is noisy, as is the signal from the back plate. This mode of discharging appears to be related to the "zenering" (dropping to a less negative potential) observed by Inouye and Sellen (ref. 7).

Figure 4 shows this relatively slow, sometimes repetitive discharge. During a discharge the potential of the interconnect would drop over a time scale of milliseconds to seconds. It would then rise, recharging to nearly the nominal potential over something on the order of 10 sec. before discharging again. The change in potential during the discharge indicates that about 10% of the charge on the array is lost. Up to half of the charge may be lost at the initiation of zenering.

Because these discharges could not be reproduced reliably, the conditions necessary for their existence are difficult to establish. So far, the following have been observed:

1) There is a dependence on beam current density.
2) These discharges have not been seen at beam energies of 3 KeV or less, breakdowns are more frequent at higher beam energies.
3) The incident beam angle also appears to influence this discharge mode, since these discharges have not been seen at a normal angle of incidence.

2. Fast Discharges.

Faster discharges were also seen on the floating array (Fig. 5). The conditions under which they occur are shown in Table II. These discharges are less frequent than the slower discharges and, since the interconnects maintain a constant potential between discharges, are essentially single events. During these single discharges, the interconnect potential drops 100 to 2000

volts (both minor and major events occur). During a minor transient observed on the back plate, the discharge lasts a few tenths of a millisecond (the rise time in figure 5). The current from the array is on the order of a micoamp. The change in voltage, obtained by multiplying the peak of the back plate signal by the ratio of cable capacitance to back plate capacitance, indicates that the voltage change is about 50 to 100 V, consistent with the change in interconnect potential seen by the Trek probe. Such a minor discharge accounts for 4% of the total charge on the array. A major discharge can result in a 90% loss of charge. The current during these discharges was too high for the instruments to measure.

Only the major discharges are visible. These produce a dim flash of light over all of the solar cells. The intensity is comparable to the glow when the cover slides are bombarded with an intense electron beam. This indicates that the entire array is involved in the discharge. However, the conditions which initiate the discharge, may be an as yet, unknown local effect.

However, from Table II the following conclusions are drawn:

1. Fast discharges are more easily produced at higher beam energies.
2. Large discharges are associated with more normal angles of incidence and lower beam current densities.
3. Small discharges are associated with higher angles of incidence and higher beam current densities.

One major conclusion can be drawn from these observations. The inverse potential gradient is not a fundamental prerequisite for discharges. However, further conclusions must be tentative. It is not clear whether the discharges are due to an interaction with the electron beam or with a weak plasma generated by the ion pump or even gas ionized by the electron beam.

In work conducted after the above results were obtained Leung (ref. 10) was able to generate the fast discharges on a stainless steel plate with cover

slide glass attached. Therefore the fast arcs are not caused by the local geometry of the interconnect region. We believe that the fast arcs are related to the arcs seen on biased arrays, and those seen in plasma.

Leung did not see the slow discharges. This de-charging process might be due to a mechanism coupling the interconnects to the pumps/wall. If the mechanism which allows access to the high resistance caused by the ion pump can be switched on and off, it might result in these discharges.

C. Biased Array

The solar array interconnects of this floating array can be biased negative to produce an inverse potential gradient and explore its relationship to discharges. Discharges were observed on the array using the back plate with the interconnects biased to -2 KeV (Fig. 6). The back plate may be used to monitor changes in the interconnect voltage as the power supply becomes over loaded and the potential of the interconnects falls. This is shown in Fig. 6 by the increase in the back plate voltage.

An electron beam energy of 2 KeV incident on the array at an angle of 45 degrees, pushed the cover slides to -800 V. The power supply keeps the potential of the interconnects constant, until it becomes overloaded during a discharge. After the power supply overloads the back plate sees a current from the array of 10 mA, estimated from the rate of increase of the voltage, and assuming a capacitance to ground of 500 pF. This capacitance is primarily due to the cable between the power supply and the array. The power supply can handle only 5 mA. The instrumentation did not have the range to see the top of the curve. The decay of the transient is the RC time constant for the back plate/cable since the power supply takes several milliseconds to recover from the overload.

After the discharge the cover slide potential is nearly equal to the interconnect potential, so at least some of the charge is being redeposited on the surface of the cover slides. No attempt was made to locate a precursor

in the back plate signal, which could have indicated charge being deposited on the cover slides.

Though this experiment supplies some information on the conditions for discharge, the characteristics of the array breakdown are swamped out by the additional charge supplied by the power supply. The initial stages of the discharge cannot be sensed because the power supply replenishes the charge lost through the discharge. Also, because the power supply increases the amount of charge available for the discharge, through the large cable capacitance, the discharges are more violent than they might otherwise be.

However, some interesting features were observed by using the four 10 cm^2 beam current sensors located about 3 cm from each corner of the array. If the electron beam is turned off after charging the cover slides, the beam sensors continue to detect a small current on the order of 1 nA (compared to a beam current of 10 nA). This increases to 2.1 nA over 500 s when a discharge occurs. (These numbers are from a specific example and are included to give an idea of the size of the effect, rather than to indicate the reproducibility of the effect.) Before some discharges, the grounded shield grid of the electron gun saw currents of up to 5 microamps, even though the electron gun was off. What is happening is not understood, but it looks as if charge is being emitted from a site. This emission increases until something gives and the discharge occurs, perhaps related to a thermal run-away mechanism. After the discharge the beam sensors detect no current. The mechanism could be related to plasma generated by the ion pumps. The high resistance indicating the plasma's existence could provide the mechanism for the initial emission. The conclusion drawn from this observation is that conditions which produce emission are a prerequisite for discharges.

Photographs of the discharges indicate several sites associated with each discharge. A flash usually occurs at a solar cell edge, either the

interconnect or another edge. In some photographs a second flash appears at the interior of a cover slide, or on the Kapton surrounding the array, or at the grounded clamps used to hold the array.

IV. SUMMARY

This experiment allows the study of discharges from an electrically floating array. Discharges can be stimulated by irradiating the array with a monoenergetic electron beam at various angles of incidence. However, these discharges are not caused by having the interconnect potentials more negative than the cover slide potentials.

Various modes of discharge were seen. A relatively slow, repetitive discharge is seen at low electron densities which lasts a few milliseconds to seconds. These discharges release about 10% of the charge on the array. Single, faster discharges are also seen which release currents on the order of microamps, for a few tenths of a millisecond. Minor discharges emit about 4% of the charge, while major discharges emit about 90% of the charge stored in the array.

The slow and fast minor discharges are smaller than the discharges induced by biasing the interconnect negative with respect to the cover slides. The power supply and the associated cable provide additional charge which allows much more intense discharges.

The potential gradient at the interconnect is not the sole criteria for discharges to occur. In the floating array the interconnect potentials are slightly positive with respect to the cover slides. However, there is a region at the edge of the cover slide which is more negative than the center of the cover slide. This work has produced data showing how charge is deposited on the array by an electron beam.

An observation was reported which indicates that electron emission takes place on the biased array. This emission may be a prerequisite for the fast

discharges, and may be the mechanism for the slow discharges.

Further study is needed to determine more precisely the threshold conditions for these discharges. The angle of incidence effects, current density, and electron beam energy effects need to be determined. The difficulty in reproducing discharge conditions indicate that the history of the array may be important, and that contamination of the surfaces may influence the conditions for initiating these discharges.

Preliminary calculations with the NASCAP program indicate that portions of the system studied here could be usefully modelled, employing secondary electron yield results obtained at CWRU on similar surfaces. More detailed calculations could provide further understanding of the processes involved.

References

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Table I. Slow Discharges

8 KeV Beam

Angle of Incidence

Current Density (nA/cm^2)	0	20	40	55	70
2.5	None		3/500s		None
3.0		None			
3.5	None	1/600s	10/300s		None
4.0				1/2000s	
4.5	None				3/2100s
5.0		2/600s			
6.0		None		None	
7.0		None		None	
8.0				None	
>10.0		None			

6 KeV Beam

Current Density (nA/cm^2)	0	20	40	55	70
2.0			10/300s		None
2.5		None	1/400s	1/500	
3.0		None	8/400s		None
3.5	None				
4.0	None	7/600s			None
5.0		9/600s			None
6.0		2/600s			
8/0				3.200	
>8.0	None		13/400s		

Table II. Fast Discharges

8 KeV Beam

Current Density (nA/cm^2)	Angle of Incidence: 0	20	40	55	70
2.5	large		large		none
3.0		large			
3.5	large	noisy	small		none
4.0		large		noisy	
4.5	small				small
5.0		large			
6.0		large		small	small
7.0		small			
8.0				large	
>10.0		small			
fast discharge rate	7/3000s	9/8000s	8/1200s	1/2400s	2/4000s
6 KeV Beam					
2.0			none		none
2.5		noisy		small	
3.0		large	large		none
3.5	none			small	
4.0	none	both			small
4.5					small
5.0		small			
5.5	small				
6.0		small			
>8.0	small		small	small	
rate	2/2200s	6/5000s	3/2750s	2/700s	3/3300s
4 KeV Beam					
2.0					none
2.5			none	small	
3.0			none		none
4.0			none		none
5.0			none		
7.0			none	small	
8.0			none		
rate			0/6000s	2/1900s	0/2800s1

Publications based on this work

D. B. Snyder, "Environmentally Induced Discharges on a Solar Array", IEEE Transaction on Nuclear Science, NS-29, 1607 (1982).

Personnel

During the grant period, D. B. Snyder was a Research Associate at Case Western Reserve University carrying out some aspects of the material characterization at CWRU while using one of the large ion pumped vacuum systems at NASA LeRC as well as the computing capabilities available with NASCAP there.

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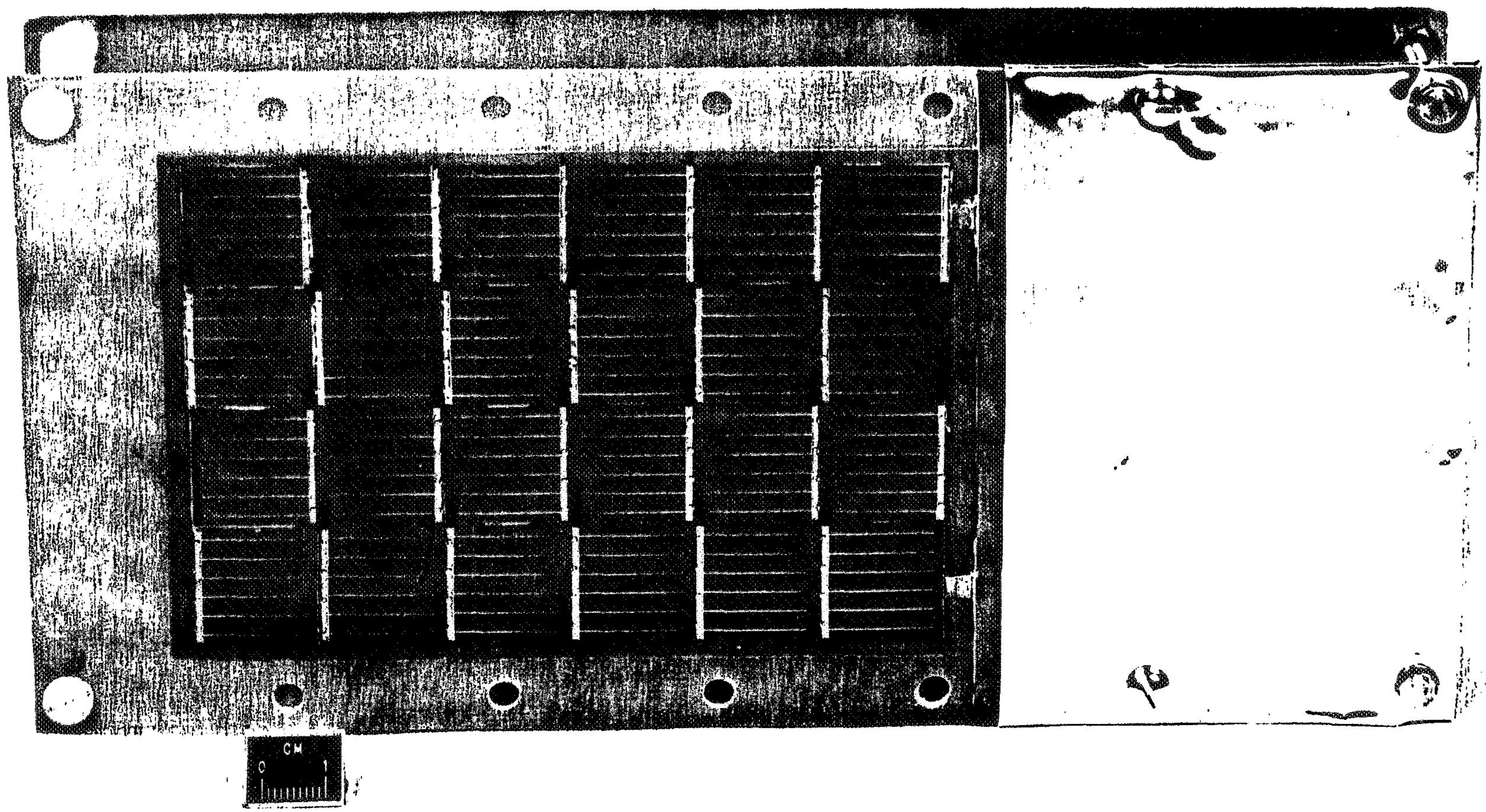

Figure 1

EXPERIMENT SCHEMATIC

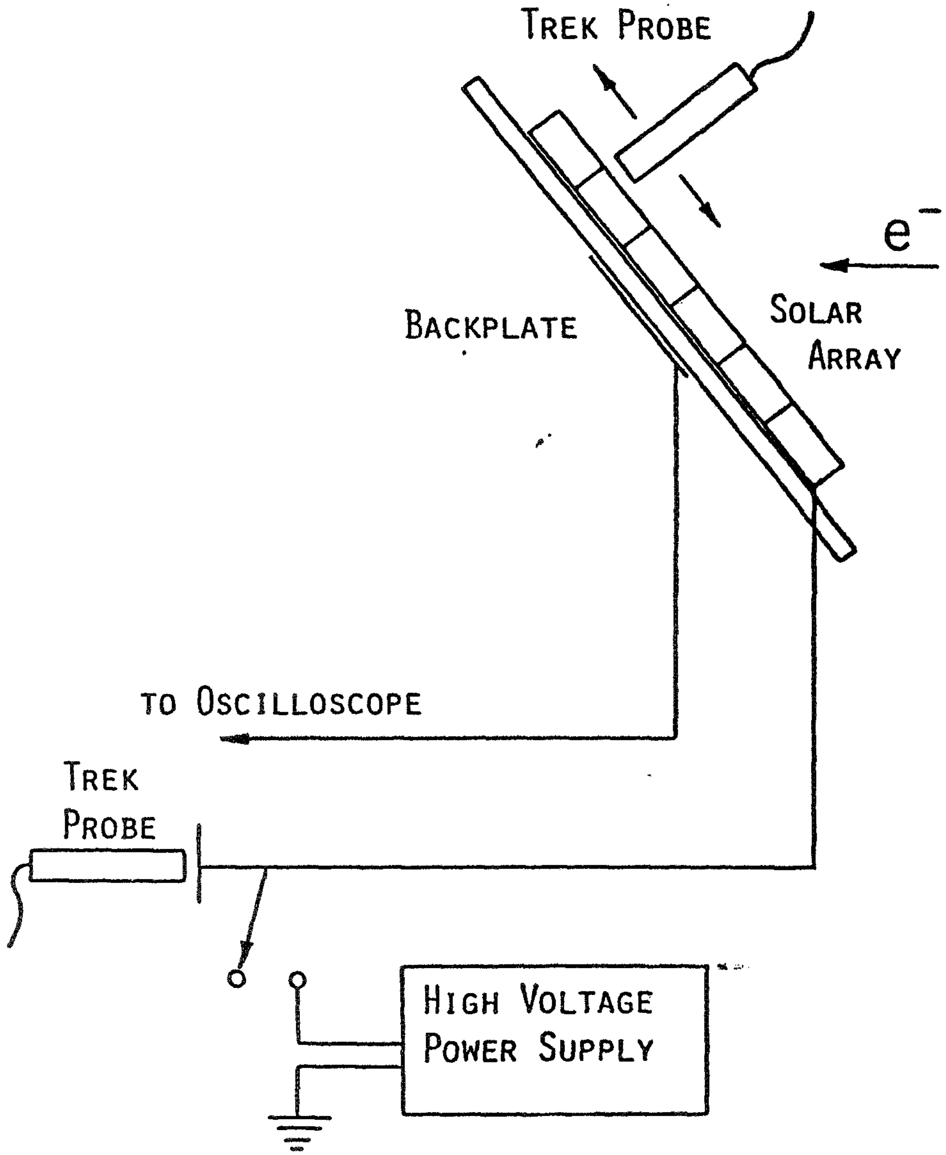

Figure 2(a)

RESPONSE OF BACK PLATE TO A SQUARE PULSE

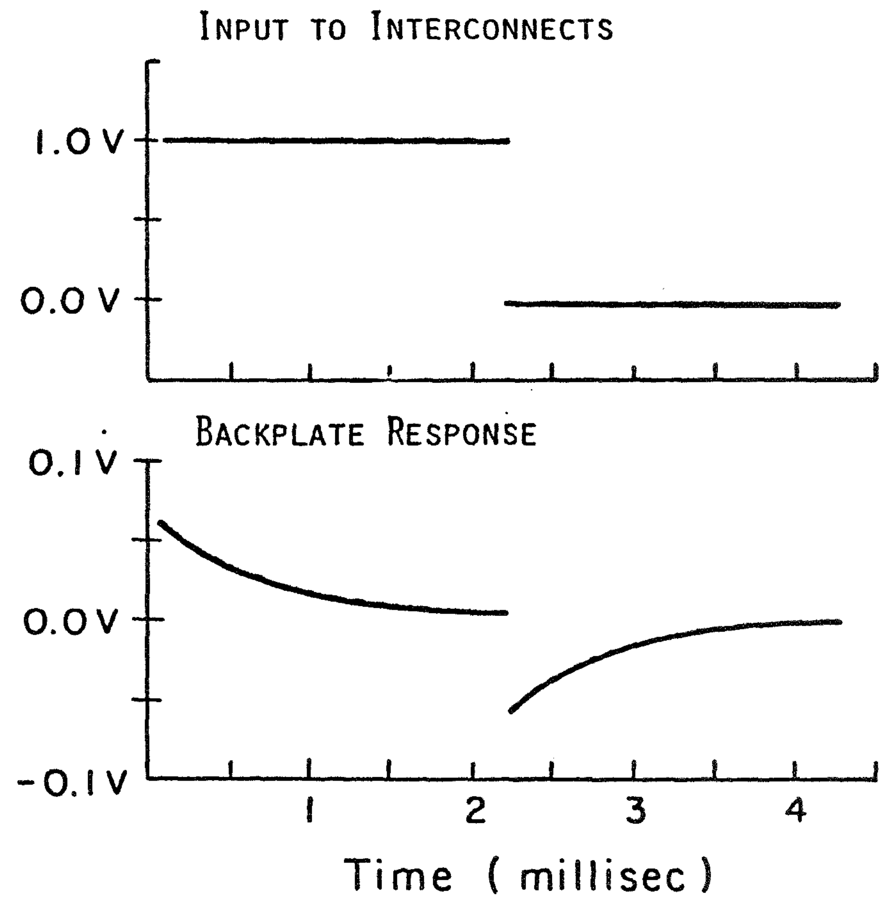

Figure 2(b)

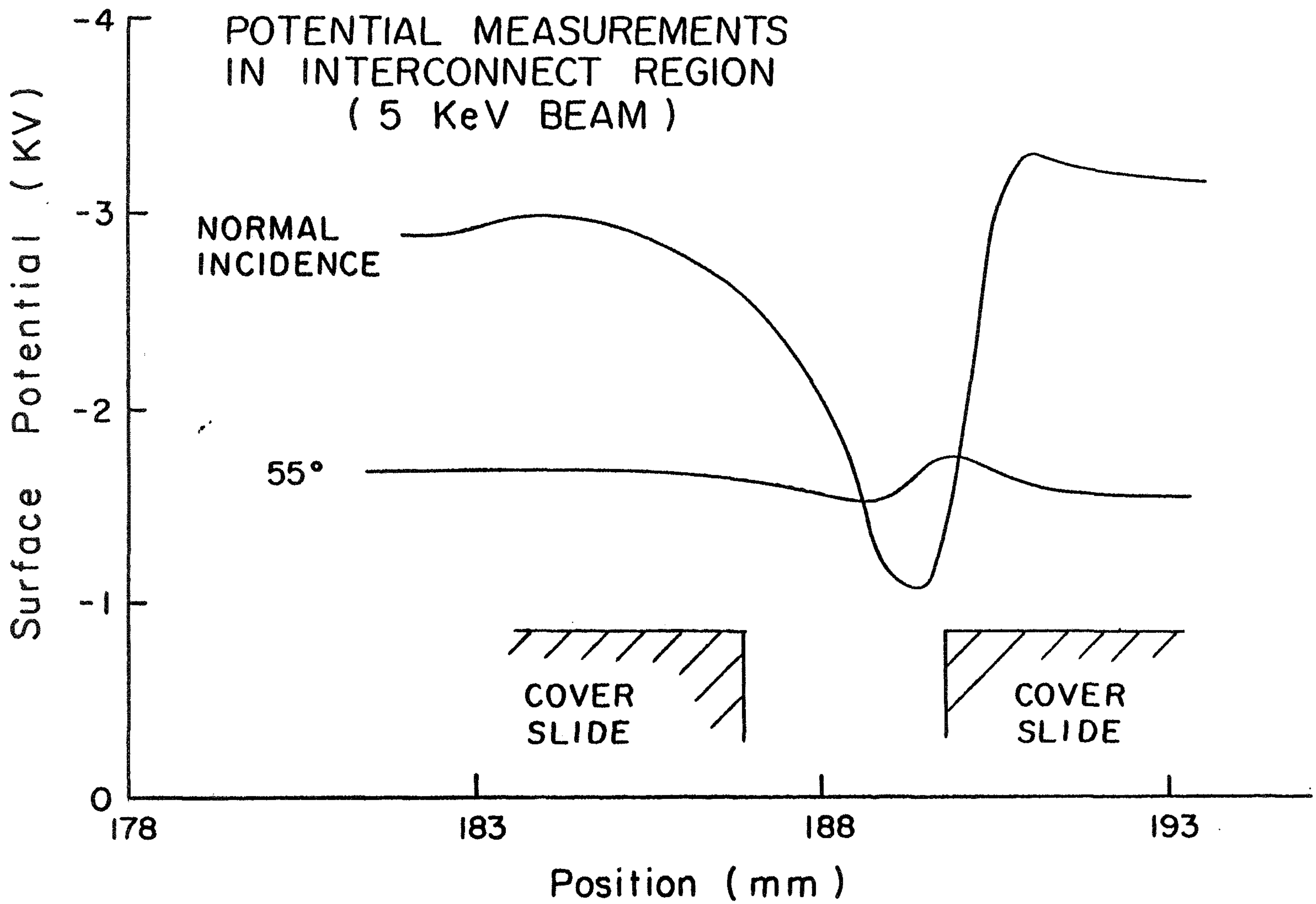
POTENTIAL MEASUREMENTS
IN INTERCONNECT REGION
(5 KeV BEAM)
NORMAL
INCIDENCE
55°
COVER
SLIDE
COVER
SLIDE
Surface Potential (KV)
-4
-3
-2
-1
0
178
183
188
193
Position (mm)

Figure 3

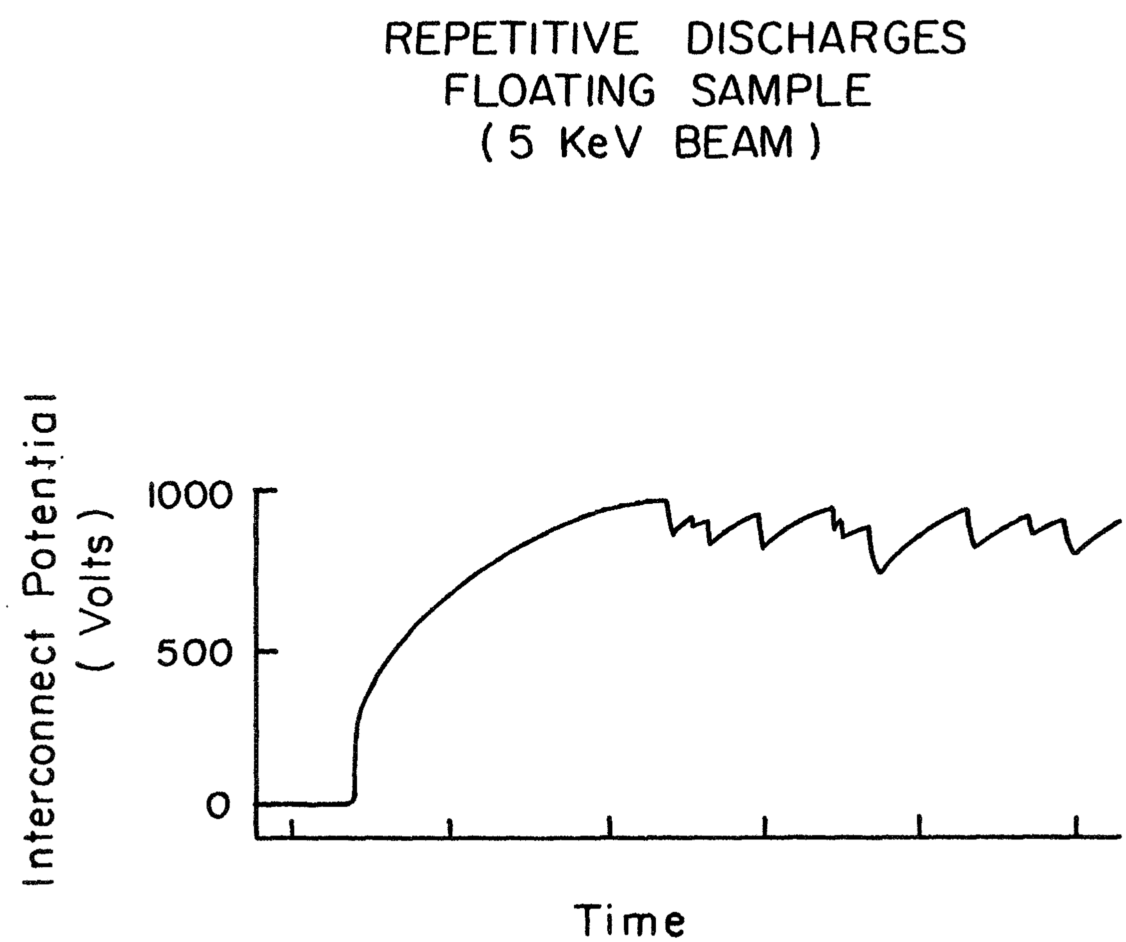
REPETITIVE DISCHARGES
FLOATING SAMPLE
(5 KeV BEAM)
Interconnect Potential
(Volts)
1000
500
0
Time

Figure 4

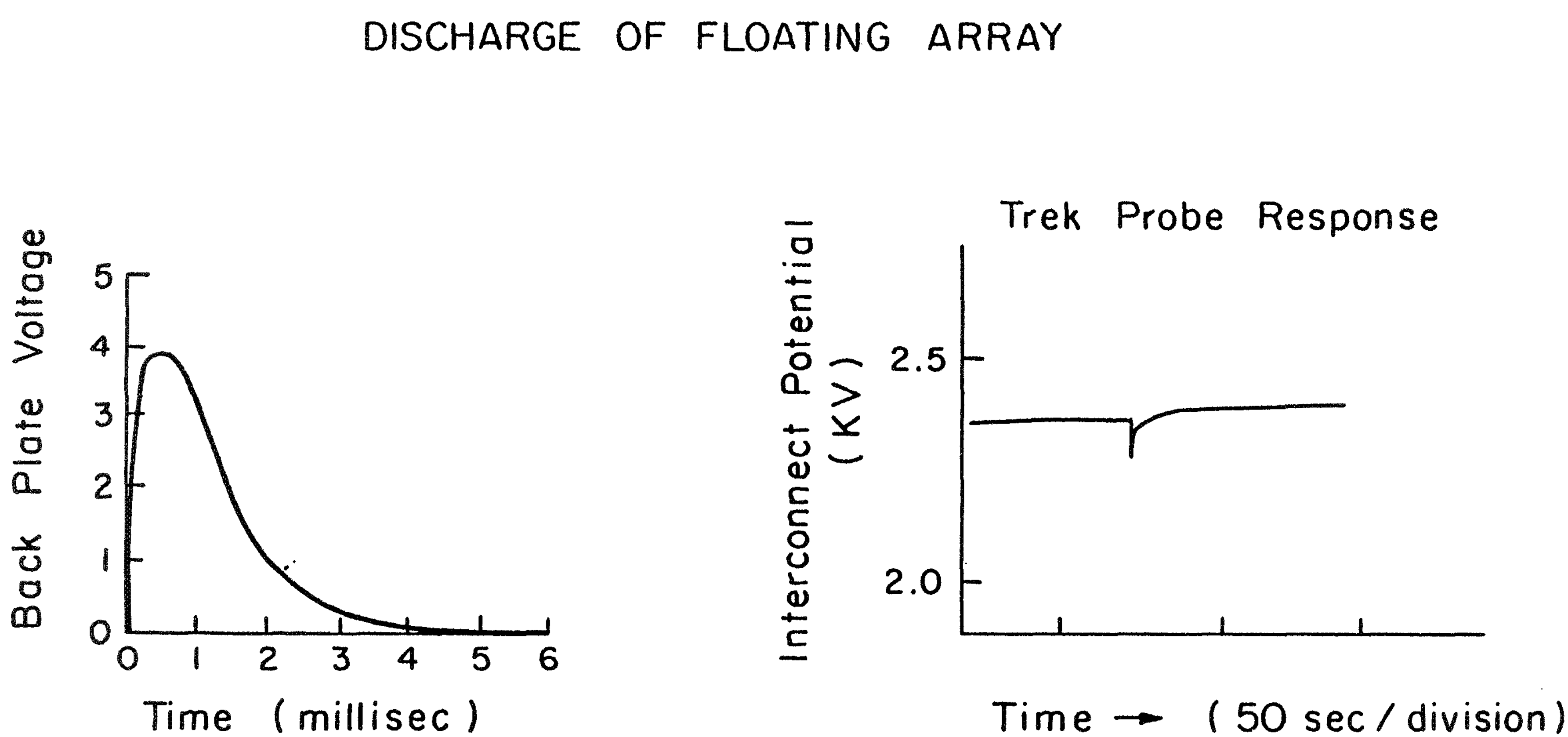
DISCHARGE OF FLOATING ARRAY
Back Plate Voltage
5
4
3
2
1
0
0 1 2 3 4 5 6
Time (millisec)
Trek Probe Response
Interconnect Potential (KV)
2.5
2.0
Time → (50 sec / division)

Figure 5

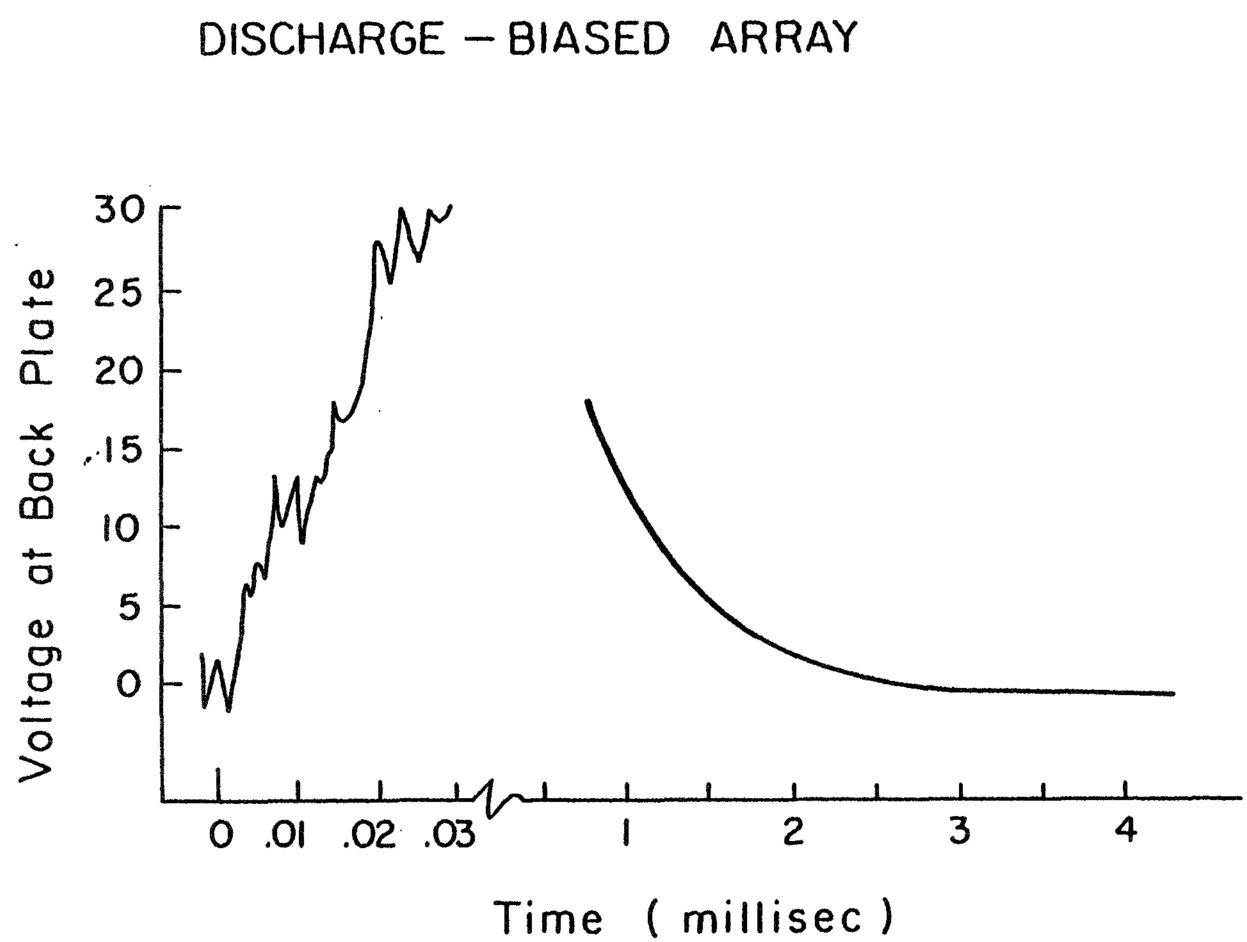
DISCHARGE – BIASED ARRAY
Voltage at Back Plate
30
25
20
15
10
5
0
0
.01
.02
.03
1
2
3
4
Time (millisec)

Figure 6